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TECHNICAL NOTE 3483

AN ANALYSIS OF ACCELERATION, AIRSPEED, AND GUST-VELOCITY
DATA FROM A FOUR-ENGINE TRANSPORT AIRPLANE IN
OPERATIONS ON AN EASTERN UNITED STATES ROUTE

By Thomas L. Coleman and Mary W. Fetner

Langley Aeronautical Laboratory
Langley Field, Va.



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SUMMARY

Time-history data obtained by the NACA VGH recorder from one model of a four-engine civil transport airplane during operations on an eastern United States route are analyzed to determine the magnitude and frequency of occurrence of gusts, gust accelerations, and the associated airspeeds. The results of the analysis are compared with results previously reported for two similar operations involving other types of four-engine transports. The gust-load history for the present operation is indicated to be more severe than that for the other two operations. The present airplane was operated in rough air at a higher percentage of its design speed than were the other airplanes and this condition was primarily responsible for the more severe load history for the operation.

INTRODUCTION

For a number of years, studies of the gusts and gust loads experienced by transport airplanes have been made by the National Advisory Committee for Aeronautics through use of airspeed, altitude, and acceleration measurements taken during routine airline operations. This information in the past has proven useful in the formulation of design requirements, in the studies of fatigue problems, and in the prediction of gust and gust-load histories for new types of operations. The present report represents a continuation of this work and presents an analysis of the gust velocities, gust accelerations, and the associated airspeeds for operations of a four-engine transport airplane on routes in the eastern United States. The acceleration and gust histories are compared with those obtained in references 1 and 2 for two other types of four-engine transports operated on two different transcontinental routes. In order to obtain an estimate of the overall gust history for the operation, data previously obtained from the NACA V-G recorder on the present route are used in conjunction with the data from the NACA VGH recorder.

APPARATUS AND SCOPE OF DATA

The data were obtained with an NACA VGH recorder which is described in detail in reference 3. The instrument yields a time-history record of the indicated airspeed, pressure altitude, and normal acceleration for each flight of the airplane.

The model of the airplane from which the data were obtained has been widely used on domestic and international routes since about 1950. The characteristics of the airplane which are pertinent to the evaluation of the data are given in the following table:

Design gross weight, W, lb	107,000
Wing area, S, sq ft	1,650
Aspect ratio, A	9.17
Mean aerodynamic chord, \bar{c} , ft	14.67
Slope of lift curve, a, per radian (computed from $\frac{6A}{A+2}$)	4.93
Design cruising speed indicated, V_C , mph	271
Design speed for maximum gust intensity indicated (computed according to ref. 4), V_B , mph	187
Design never-exceed speed indicated, V_{NE} , mph	324
Gust-alleviation factor K for gross weight (ref. 4)	1.21
Limit-gust-load factor (computed according to ref. 4)	2.31

The values listed in the table were obtained from the manufacturer's design data unless otherwise indicated. The slope of the lift curve was computed from the relation $\frac{6A}{A+2}$ in order to be consistent with most past evaluations of gust data. (For example, see refs. 1 and 5.) The limit-gust-load factor of 2.31 was computed according to current Civil Air Regulations (ref. 4). This value is based on a gross weight of 107,000 pounds and an effective gust velocity U_e (ref. 6) of 30K feet per second at the design cruising speed V_C of 271 miles per hour. Although the limit-gust-load factor was calculated to be 2.31, the airplane was designed to the minimum maneuver-load factor of 2.5 as required by regulations.

The data sample represents 594 flights totaling 1,038 flight hours of routine commercial transport operation from August 1951 to August 1953. On these flights, the airplane was used for passenger operations generally on routes in the eastern United States. Flights averaged about 1.7 hours in length and, although the average cruising altitude was about 12,000 feet, altitudes of about 20,000 feet were attained occasionally.

EVALUATION OF RECORDS AND RESULTS

The VGH records were evaluated essentially in accordance with the methods used in reference 7 to obtain frequency distributions of gust accelerations, airspeeds, and altitudes.

For evaluating the acceleration data, the steady-flight position of the acceleration trace was used as a reference from which the gust accelerations were read. Only the maximum value was read for each deflection of the acceleration trace greater than a threshold of $\pm 0.3g$ from the reference. The results are summarized in table I in terms of the number of accelerations within $0.1g$ intervals for the total flight time and for the portions of the record that the airplane was considered to be in the climb, en-route, or descent condition. The climb condition covered the time from take-off until the airplane began to maintain level flight as was indicated by the altitude trace of the record. The descent was considered to begin when the airplane began to lose altitude consistently and to end when the airplane touched down. The portion of the flight between the climb and descent was considered to be the en-route condition and ordinarily contained some en-route changes in altitude. The flight hours, flight miles, and number of accelerations per mile for each distribution are also noted in table I.

Figure 1 presents the acceleration data for the total sample in terms of the average number of accelerations that exceeded given values per mile of flight. The ordinate values for the figure were obtained from table I by progressive summation (starting with the frequency for the largest a_n) of the total-frequency distribution and then division of each sum by the total flight distance. The solid line in the figure was faired to represent the data.

In order to compare the present results with results obtained from other similar types of operations, the acceleration distributions for operation C of reference 1 and operation A of reference 2 also are shown in figure 1. The operations represented by the data from references 1 and 2 are similar to the present operations in that they both involved four-engine transport airplanes used in domestic medium-altitude operations on flights which averaged about 2-hours duration. For convenience of comparison, some of the pertinent features of the operations are summarized in table II.

Transport airplanes are designed for different load factors depending upon their particular characteristics and, therefore, the acceleration distributions given in figure 1 cannot be used directly to compare the gust loads on the different airplanes. In order to compare the gust-load histories for the different airplanes, the acceleration distributions of figure 1 are given in figure 2 as a ratio of the measured acceleration a_n

to the acceleration $a_{n_{LIF}}$ corresponding to the computed limit-gust-load-factor increment for each airplane. The values of $a_{n_{LIF}}$ were computed according to current Civil Air Regulations (ref. 4) and were based on the design gross weight and the design cruising speed V_C for each airplane. The values of $a_{n_{LIF}}$ used in obtaining figure 2 were 1.18g and 1.54g for the data from references 1 and 2, respectively, and 1.31g for the present data.

In order to determine the gust velocities encountered during the present operations, the airspeed and altitude corresponding to each gust acceleration in table I also were read from the VGH records. These values were then used to calculate the derived gust velocities U_{de} by means of the gust equation discussed in reference 6. In these calculations, an average operating weight of 0.85 design weight and a mass parameter corresponding to the midpoint for each 5,000-foot-altitude interval was used. The results are summarized in table III for the total sample and for the given pressure-altitude intervals together with the pertinent flight hours and flight miles. It should be noted that, because of the use of the revised gust-load formula, the derived gust velocities U_{de} are higher by a factor of roughly 1.6 for the same turbulence than the corresponding effective gust velocities U_e computed in past analyses of airline gust data. (See, for example, ref. 7.)

The gust-velocity distribution for the total sample from table III is plotted in figure 3 to represent the average number of gusts that exceeded given values per mile of flight. The solid line in the figure is faired through the data to indicate the trend of the distribution. The apparent dropoff in gust frequency at the lowest gust velocity is due to incomplete frequency counts near the reading threshold. For comparison, the distributions of gust velocities U_{de} for the two other operations (refs. 1 and 2) previously mentioned also are indicated in figure 3.

Past analyses of VGH data have shown a large decrease in the frequency of occurrence of gust velocities with increasing altitude. In order to determine the variation in gust frequency with altitude for the present operations, the gust data from table III are plotted in figure 4 by 5,000-foot-altitude intervals.

For purposes of examining the airspeed practices, distributions of indicated airspeed for the climb, en-route, and descent conditions were obtained simply by reading the airspeed trace at 1-minute intervals for each flight. These distributions are given in figure 5 as the percent of the time spent within given airspeed intervals of 10 miles per hour for each flight condition. In order to compare these data with the

airspeeds used in rough air, the distributions of airspeeds for those portions of the records in which gust accelerations greater than $\pm 0.3g$ were experienced are shown in the figure by dashed curves. The flight speed for maximum gust intensity V_B and the design cruising speed V_C are also indicated in figure 5.

The accuracy of the data presented herein depends on the inherent instrument errors, installation errors, and reading errors. The inherent instrument errors and a general discussion of installation errors are given in reference 3. A discussion of reading errors applicable to the present data is contained in reference 7. The VGH installation met the basic installation requirements given in reference 3; consequently, it is felt that the installation errors for the present data are negligible. The estimated maximum error for each of the quantities measured is given below:

Acceleration, g	± 0.05
Airspeed, mph	± 5
Altitude, ft	± 300

Based on considerations of the sample size (1,038 hours) and past work on the reliability of results of the type presented, the distributions of accelerations (fig. 1) and gust velocity (fig. 3) are estimated to be reliable within a factor of about 2 (on the ordinate scale) at the smaller acceleration and gust-velocity values and within a factor of about 3 at the higher values. These factors represent spreads of roughly 20 percent in the value of the acceleration and gust velocity for a given frequency of occurrence.

The effect of dynamic response on the accelerations measured at the center of gravity of the airplane in the present investigation is unknown and is not accounted for in either the acceleration or gust data. Where results from other investigations are compared with the present results, it is assumed that dynamic response would not appreciably influence the comparison since the airplanes were of the same configuration and of about the same size.

DISCUSSION

Gust Velocities

Figure 3 shows that gusts of given velocities are about twice as frequent for the present operation as for operation C of reference 1 and from three to five times as frequent as for operation A of reference 2. These variations in the gust experience on the three routes do not appear to be unusual in that they are no larger than the differences commonly found between different routes. (For example, see refs. 1

and 2.) The differences among the gust experiences may result from a combination of several factors, such as actual differences in the amount and intensity of rough air on the three routes, differences in operating practices in regard to turbulence avoidance, or possibly from sampling fluctuations as discussed previously. The detailed information necessary to resolve the differences in the gust experiences is not available.

Comparison of the distributions of gust velocities for various altitudes in figure 4 shows a large decrease in gust frequency with increasing altitude, particularly in regard to gust velocities below about 30 feet per second. For example, gusts greater than 15 feet per second were encountered about seven times as frequently below 5,000 feet as in the 10,000- to 15,000-foot altitude bracket. Little difference is noted, however, in the frequency of occurrence of the larger gust velocities for the various altitudes. This result has been noted in some previous analyses and, as suggested in reference 7, may be associated with flight through the more fully developed clouds at the higher altitudes.

Accelerations

Consideration of figure 1 shows that the shapes of the distributions of gust accelerations for the three operations are very similar and that the frequency of accelerations for the present operations is several times that for operations A and B. The differences among the frequency of accelerations for the three operations are due primarily to the variations in the gust experiences (fig. 3) and wing loadings since the average airspeeds in rough air are about equal for the three operations (table II). It may be noted that the difference between the frequencies of accelerations for the present operation and operation A is due almost entirely to the difference between the gust experiences (fig. 3) for the two operations since the wing loadings of the two airplanes are about equal (table II).

An examination of the acceleration data for the climb, en-route, and descent conditions (table I) indicates that over 50 percent of the total number of accelerations occurred during descent and that less than 10 percent occurred during climb. When compared in terms of frequency of occurrence per mile, however, the frequencies for the climb and en-route conditions are approximately equal whereas the frequency for the descent condition is four or five times higher. Consideration of the airspeeds and altitude distributions for the three flight conditions indicated that the high frequency of accelerations for the descent resulted from the combination of high airspeeds and the large percentage of time spent at very low altitude (below 4,000 feet) during descent together with the greater amount of turbulence generally found at low altitude. The accelerations experienced during the different flight conditions for the present operation conform with the results for other airline operations.

Load Histories

Comparison of the curves in figure 2 indicates that given fractions of the computed limit-gust-load-factor increment $a_n/a_{n_{LIF}}$ were exceeded about twice as frequently in the present operations as in operation C and larger differences are noted when comparison is made with operation A. For values of $a_n/a_{n_{LIF}}$ of 0.2, the frequencies were about five times those of operation A, whereas values of $a_n/a_{n_{LIF}}$ of 0.6 were exceeded about 20 times as frequently. For the three operations considered, therefore, a considerable variation exists among the gust-load histories and these variations would be of importance to the designer and operator when such a factor as fatigue life is being considered. These variations in the load histories result mainly from the airplanes having been operated in rough air at different percentages of their design speeds and, to a lesser extent, from differences among the gust velocities encountered in the three operations.

Airspeeds

Overall airspeeds.— The overall distributions of airspeed in figure 5 show that the airspeeds for the climb conditions generally were lower than those for the en-route and descent conditions and that the highest airspeeds were obtained during descent. These results are in agreement with other transport operations previously reported. The airplane normally was operated below the cruising speed V_C of 271 miles per hour during climb and en route whereas about 20 percent of the total time in descent was at speeds greater than V_C .

For comparison, the average overall airspeeds in the three flight conditions for the present operations and for operations C and A are given in the following table as a percentage of the design cruising speeds V_C .

Operation	Overall average airspeed, percent V_C		
	Climb	En route	Descent
Present	66	85	89
C (ref. 1)	61	70	77
A (ref. 2)	64	77	80

Comparison of the values in the table shows that the present airplane was operated in each flight condition at a higher percentage of its

design cruising speed V_C than the other two airplanes. The maximum differences among the average airspeeds for the three operations are 5 percent, 15 percent, and 12 percent for the climb, en-route, and descent conditions, respectively. The comparison indicates, therefore, that appreciable differences exist among the airspeed practices used in the three operations.

Airspeeds in rough air.— Comparison in figure 5 of the distributions of airspeeds at which accelerations $a_n \geq 0.3g$ were experienced with the overall airspeed distributions shows that only slight differences exist between the airspeeds for overall operations and the speeds in rough air. The airspeeds during climb were normally lower than the speed for maximum gust intensity V_B ; consequently, a reduction in airspeed generally was not necessary when encountering rough air in this flight condition. In addition, the results in figure 5 do not indicate any appreciable reduction in airspeed upon encountering rough air in the en-route and descent conditions. In order to determine whether the airspeed was reduced for the higher levels of acceleration, the VGH data were sorted to obtain the distributions of airspeeds at which $a_n \geq 0.5g$ and $a_n \geq 0.7g$ were encountered. Comparison of these airspeeds with the overall airspeeds also indicated no appreciable slowdown for the higher levels of acceleration. The results indicate, therefore, that significant airspeed reductions were not obtained prior to encountering the rough air represented in the present data. These results are in agreement with the analyses given in references 1 and 2.

In order to compare the airspeed practices in rough air for the present operations with those for operations C and A, the average airspeeds in rough air for the three operations are given by flight condition in the following table as a percentage of the design cruising speed V_C .

Operation	Average airspeed in rough air $a_n \geq 0.3g$, percent V_C		
	Climb	En route	Descent
Present	69	86	88
C (ref. 1)	65	68	77
A (ref. 2)	66	77	80

Comparison of the values in the table shows that the present airplane was operated in each flight condition at a higher percentage of its design cruising speed V_C than were the other two airplanes. The

relatively high percentage of V_G at which the present airplane was flown in rough air contributed substantially to the higher gust-load history for the operation. (See fig. 2.)

Estimated Gust History for Extended Operations

As has been noted in previous reports (for example, ref. 7), VGH data samples generally are limited in size and do not provide adequate information on the larger loads and gust velocities which occur very infrequently. In order to obtain estimates of the larger values for extended operations, therefore, recourse has been made in the past to synthesis of results from VGH and V-G data. Although V-G data are not available for the present airplane, 48,187 flight hours of V-G data taken on an earlier model of the airplane during operations on the present route are reported in reference 8. In order to obtain an estimate of the overall gust history for the operations on the present route, the gust-velocity data of reference 8 were converted to derived gust velocities U_{de} and are plotted in figure 6 together with the present VGH gust data. The solid line in the figure was faired to represent the general trend of the combined-data samples. For comparison, the estimated overall gust history for operation C of reference 1 is shown by the dashed line in figure 6.

Inspection of figure 6 shows that the maximum gust velocity from the V-G data is about twice as large as that from the VGH data. This difference between the magnitudes of the gust velocities appears reasonable when the 50 to 1 difference between the size of the two data samples is considered. Figure 6 also shows that only small differences exist between the estimated overall gust histories for the present operations and operation C.

CONCLUSIONS

An analysis of VGH data obtained from a four-engine commercial transport airplane during scheduled operations on an eastern United States route has indicated the following results:

1. Gust velocities less than about 40 feet per second were experienced twice as frequently in this operation as in operation C of NACA TN 3365, and roughly five times as frequently as in operation A of NACA TN 3475. Based on a synthesis of V-G and VGH data, there appears to be little difference between the frequency of gusts larger than about 40 feet per second for the present operation and for operation A.

2. Given fractions of the computed limit-gust-load-factor increment $a_n/a_{n_{LLF}}$ were exceeded about twice as frequently in the present operations as in operation C. In comparison with operation A, values of $a_n/a_{n_{LLF}}$ of 0.2 were exceeded about five times as frequently and values of $a_n/a_{n_{LLF}}$ of 0.6, about 20 times as frequently.

3. For these operations (covering altitudes up to about 20,000 feet), the number of gusts per miles of flight decreased significantly with increasing altitude, particularly as regards gusts less than about 30 feet per second.

4. Approximately one-half the total number of gust accelerations greater than 0.3g occurred during the descent condition.

5. There was no appreciable airspeed reduction prior to encountering the rough air represented in the present data.

6. The airspeed in rough air, expressed as a percent of design cruising speed V_C , was appreciably higher than for operations A and C. This relatively higher operating speed contributed primarily to the larger loads for the present operation.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., June 21, 1955.---

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TABLE I.- FREQUENCY DISTRIBUTIONS OF ACCELERATIONS
BY FLIGHT CONDITION AND FOR TOTAL SAMPLE

Acceleration, a_n , g units	Frequency distribution for -			Total frequency distribution
	Climb	En route	Descent	
0.3 to 0.4	188	885	1,333	2,406
.4 to .5	31	220	305	556
.5 to .6	8	89	61	158
.6 to .7	5	25	20	50
.7 to .8	3	9	6	18
.8 to .9	1	4	3	8
.9 to 1.0		2	1	3
Total	236	1,234	1,729	3,199
Flight hours	154	693	191	1,038
Average indicated airspeed, mph	180	231	241	225
Flight miles	2.8×10^4	1.6×10^5	4.6×10^4	2.3×10^5
Number of accelerations $\geq 0.3g$ per mile	8.4×10^{-3}	7.7×10^{-3}	3.8×10^{-2}	1.4×10^{-2}

TABLE II.- COMPARISON OF PRESENT OPERATIONS WITH OPERATIONS A AND C

[Four-engine transport airplanes]

Operation	Route	Weight, lb	Wing loading, lb/sq ft	Average cruising altitude, ft	Average length of flight, hr	Average indicated airspeed, mph	
						Overall	Rough air ¹
Present	North-South routes in eastern United States	107,000	64.8	12,000	1.7	225	233
C (ref. 1)	Northern transcontinental	147,000	85.5	15,700	2.03	218	232
A (ref. 2)	Transcontinental New York to Los Angeles	89,900	61.4	14,100	1.95	228	235

¹Airspeed in rough air is defined as the average speed at which accelerations $\geq 0.3g$ were encountered.

TABLE III.- FREQUENCY DISTRIBUTIONS OF DERIVED GUST VELOCITY BY ALTITUDE

Gust velocity, U _{de} , fps	Frequency distribution for altitudes of -				Total frequency distribution
	0 to 5,000 ft	5,000 to 10,000 ft	10,000 to 15,000 ft	15,000 to 20,000 ft	
8 to 12	104	17	11		132
12 to 16	1,134	501	319	37	1,991
16 to 20	474	149	116	2	741
20 to 24	127	53	34	2	216
24 to 28	43	21	15		79
28 to 32	13	6	3		22
32 to 36	4	4	3	1	12
36 to 40		2	3		5
40 to 44	2				2
Total	1,901	753	504	42	3,200
Flight hours	211	281	358	179	^a 1,038
Average indicated airspeed, mph	225	225	225	225	225
Flight miles	4.8×10^4	6.3×10^4	8.1×10^4	4.0×10^4	2.3×10^5

^aThis total includes 9 hours above an altitude of 20,000 feet.

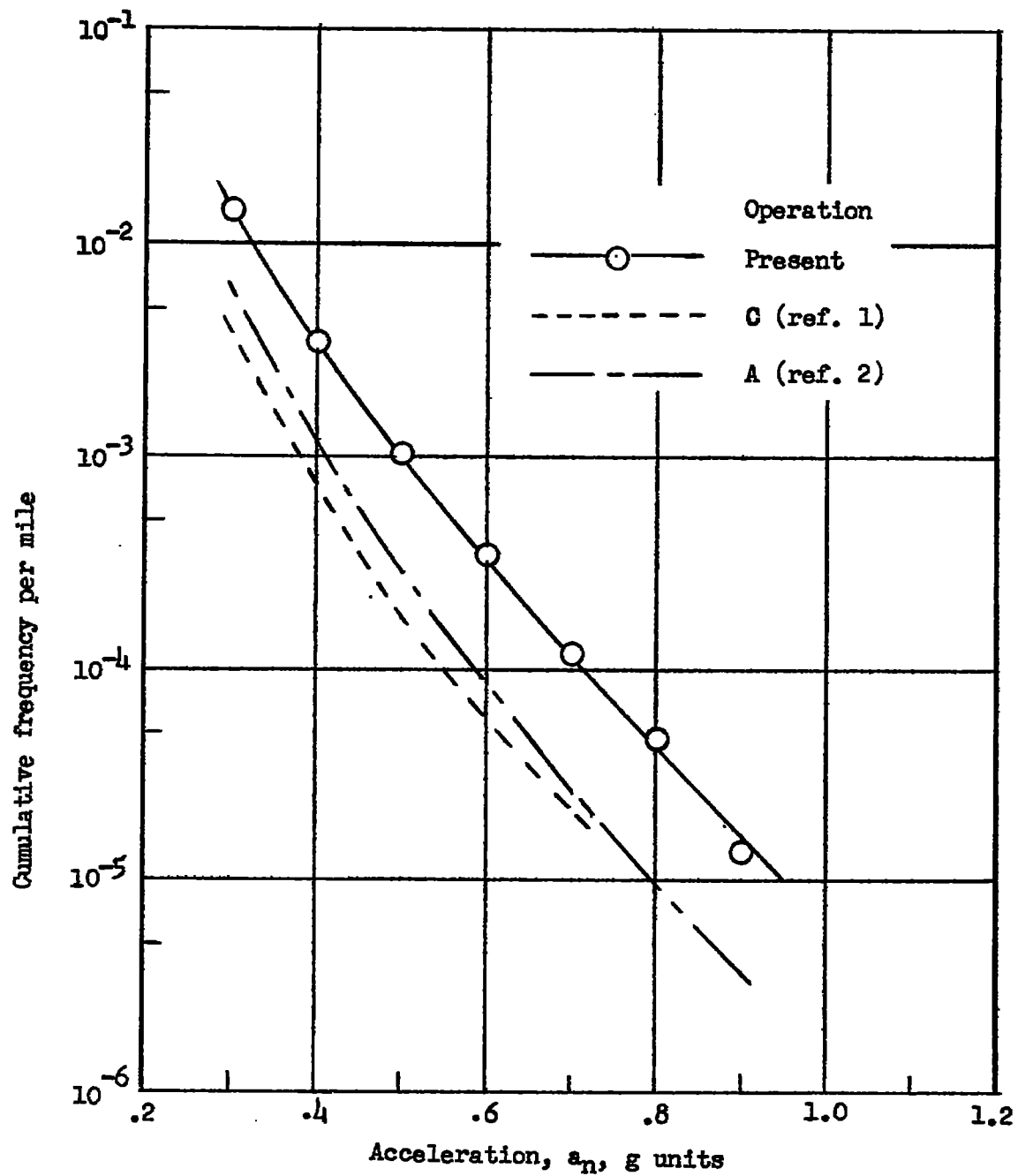


Figure 1.- Comparison of the frequency of exceeding given values of gust acceleration per mile of flight for three operations.

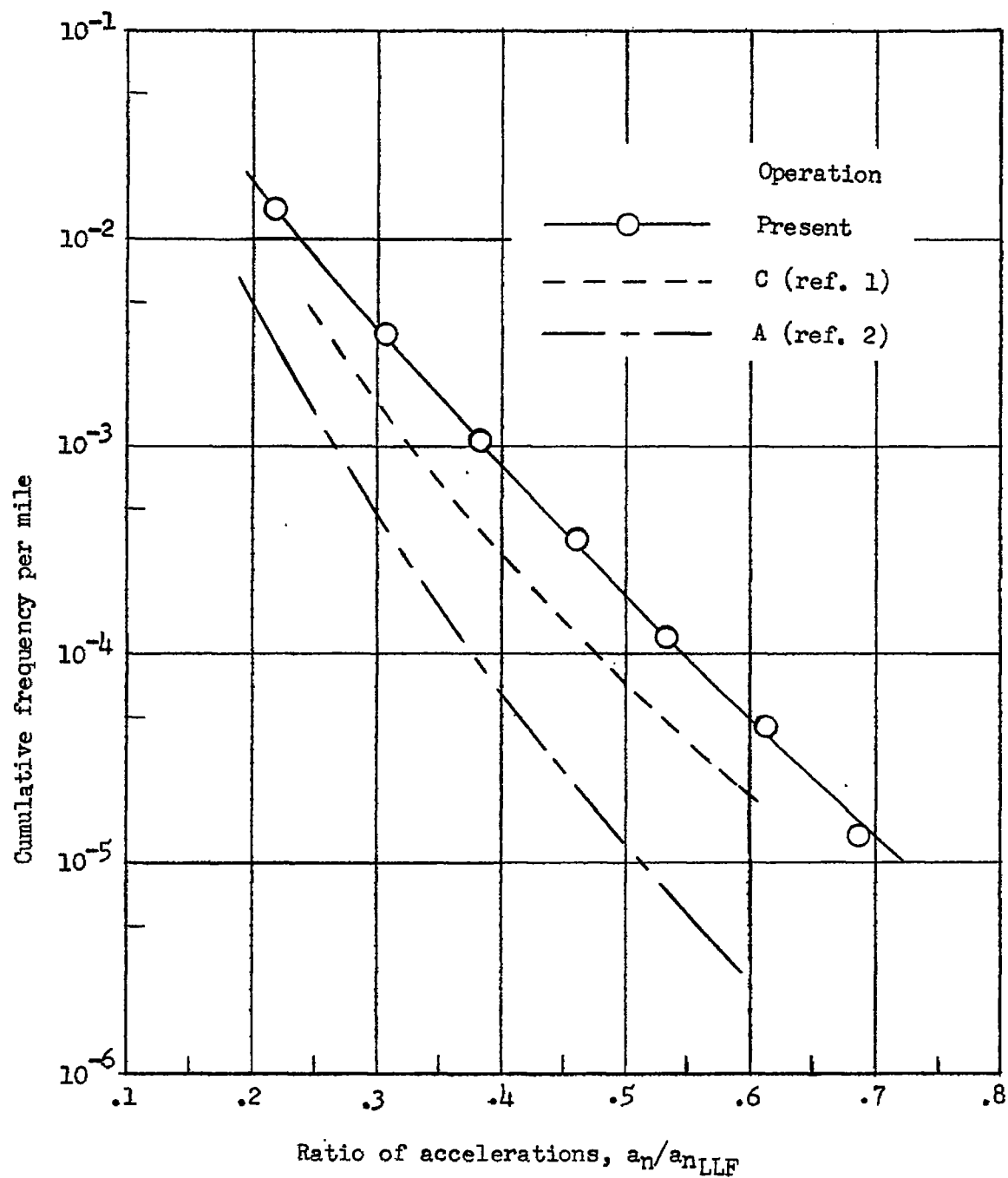


Figure 2.- Comparison of gust-load histories for three operations.

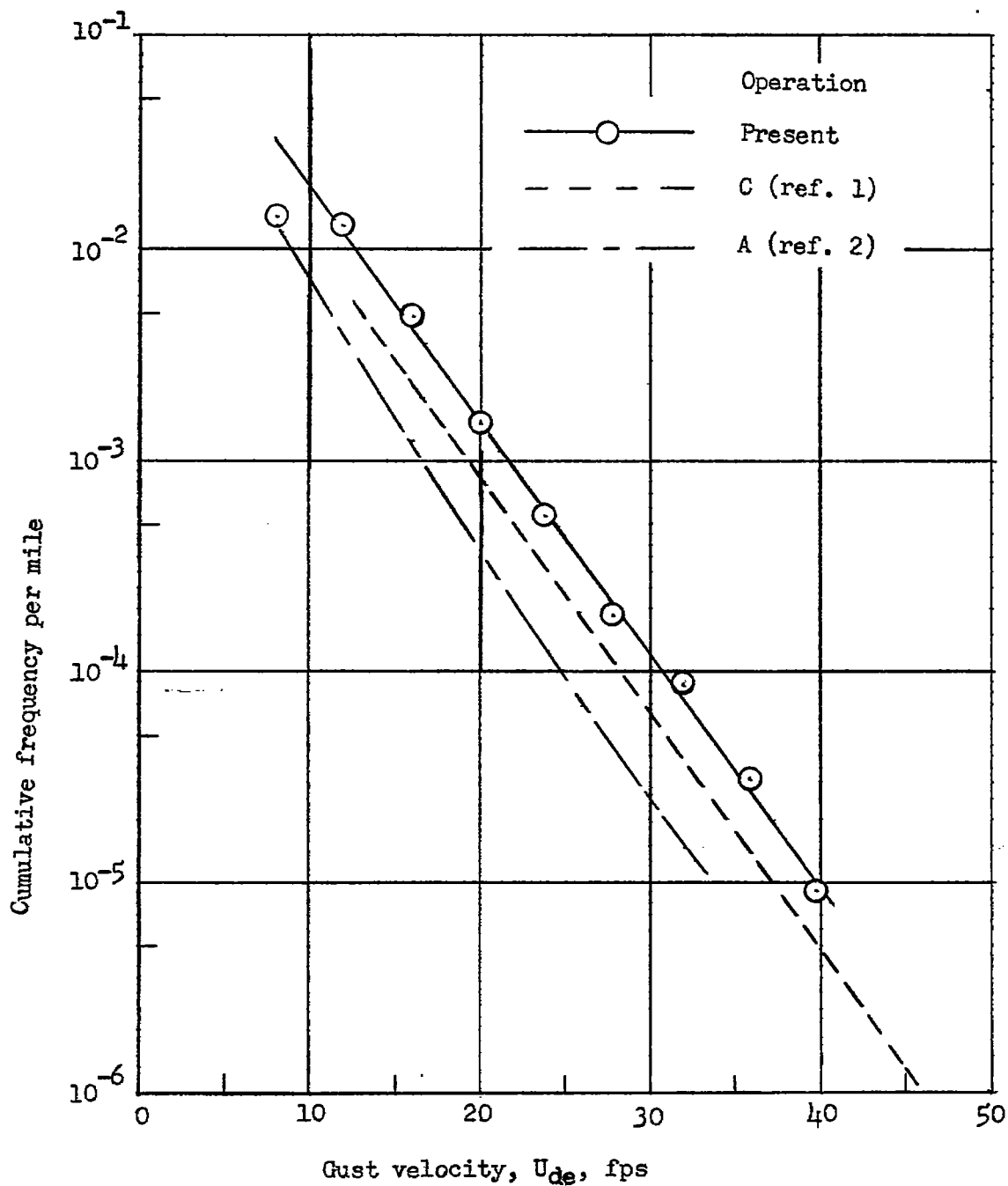


Figure 3.- Comparison of the frequency of exceeding given values of gust velocity per mile of flight for three operations.

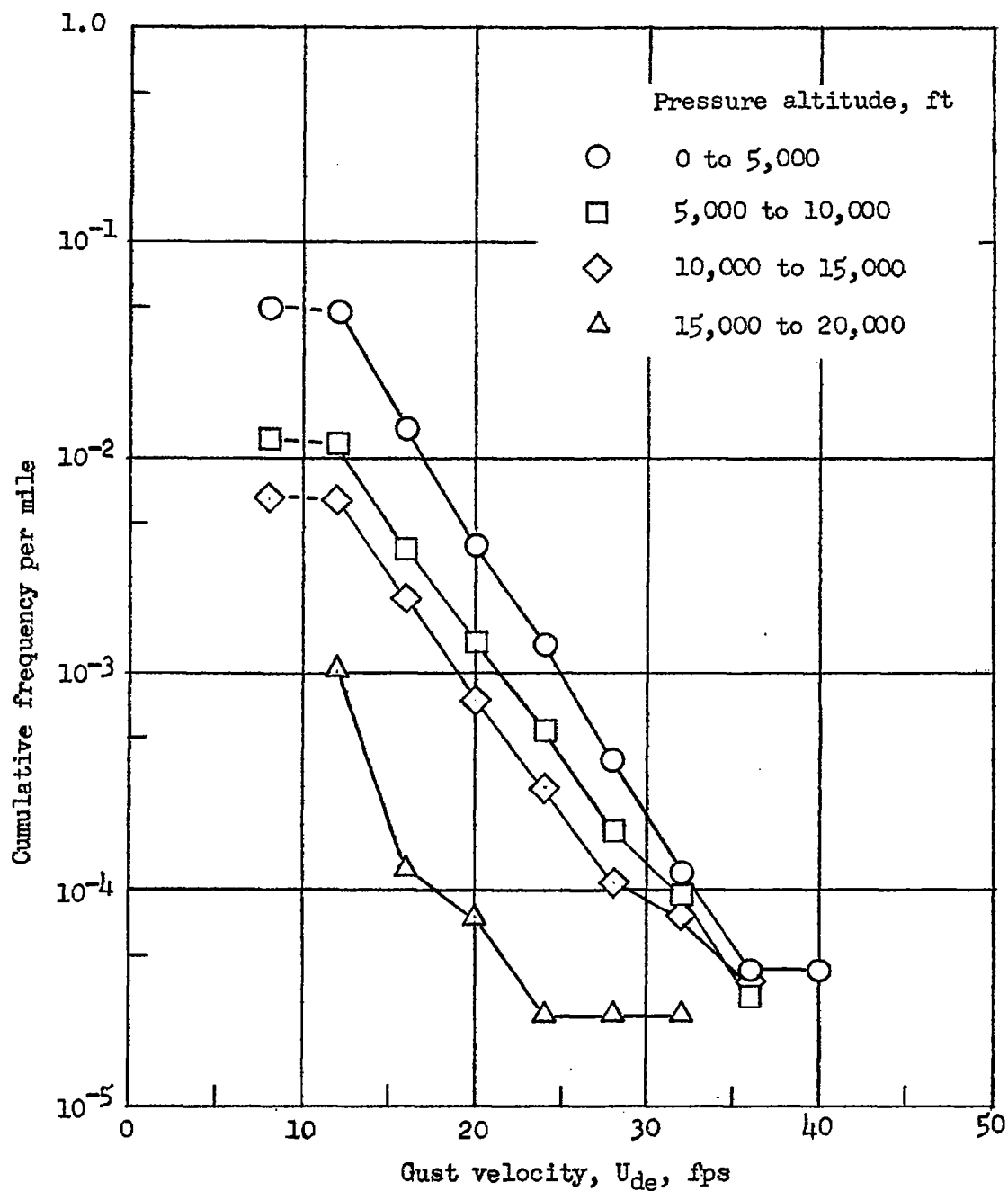


Figure 4.- Variation of the frequency of exceeding given values of gust velocity per mile of flight with pressure altitude.

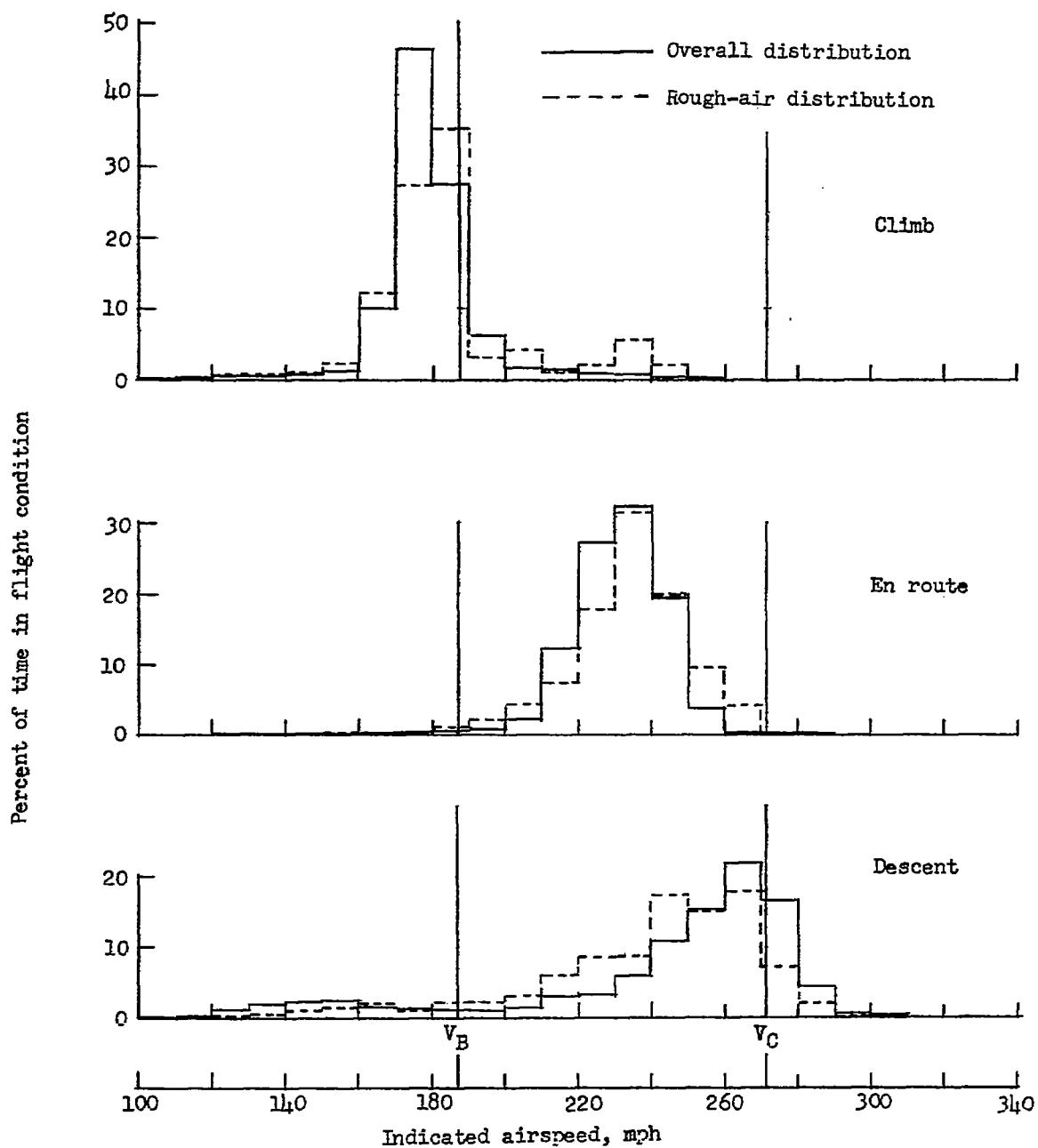


Figure 5.- Comparison of the distribution of overall airspeed with the distribution of airspeed in rough air by flight condition.

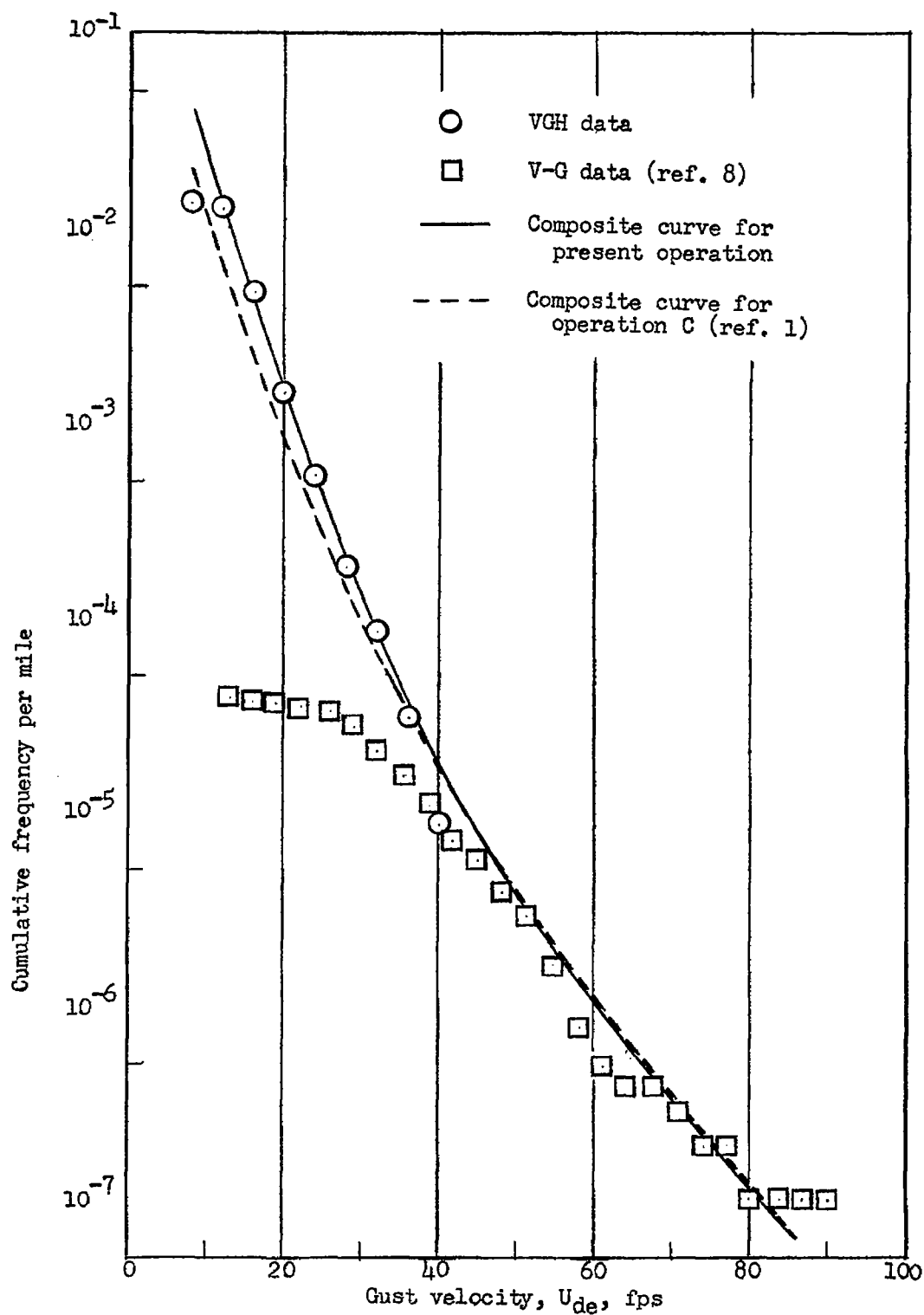


Figure 6.- Composite curve of average frequency of exceeding given values of gust velocity per mile of flight.